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THE ROLE OF LAKES IN MORAINE FORMATION, CHILEAN LAKE DISTRICT

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ABSTRACT

The nested moraines of the Chilean Lake District have been used to establish a glacial chronology for southernmost South America. This paper focuses on non-climatic controls which may have modulated the climatic signal. It presents a model for formation of the moraines around Lagos Puyehue and Rupanco where there is a nested complex dating from the last glaciation. These moraines can be divided into two types on the basis of their form, position and constituent materials: rampart moraines are broad amalgamated moraine complexes whilst ridge moraines are narrow single ridges usually located around lakeshores. Both types have lateral moraines with low up-glacier longitudinal gradients. Sections in the moraines show they are largely composed of stratified glaciofluvial sediments overthrust on their proximal flanks by clay-rich diamicts containing reworked glaciofluvial material. Despite their different characteristics, a single model explains the features of both moraine types and their location around the down-glacier ends of the lakes. Moraine formation depends crucially on the presence of a layer of water-saturated, fine, impermeable sediment in the lake basins which allows the glacier lobes to advance with negligible surface gradients, probably on a deforming bed. Although the formation of moraines requires a climatically triggered advance, their precise position is not dictated by climatic factors but by contrasts in sediment permeability and grain-size.

KEY WORDS moraine; deforming bed; Chilean Lake District

INTRODUCTION

The moraines of the Chilean Lake District on the west side of the Andes between 39° and 42°S (Figure 1) have been used to establish a chronology for the last glaciation in southernmost South America (Mercer, 1976; Porter, 1981; Lowell *et al.*, 1995). The extent of the moraines, their nested distribution around the lakes, and their location slightly north of the latitude of the present-day atmospheric polar front means that they provide an important record of climatically induced glacial fluctuations in southern South America. As the polar front shifted north during cold intervals the glaciers advanced into a peat and tree-covered landscape (Rabassa and Clapperton, 1990; Clapperton, 1993) and thus the fluctuations can be dated using radiocarbon techniques. For a glacial chronology to reflect past climate variation it is essential to assess the influence of such factors as topography on glacial advance and retreat, both in terms of the timing and the extent of the fluctuations. Thus, as part of understanding the link with climate it is necessary to study the glacial processes associated with the glacier fluctuations. Clues to these processes can be found in the morphology and sediments of the moraines. Despite extensive mapping and dating work (Brüggen, 1950; Weisschet, 1958; 1964; Olivares, 1967; Lauer, 1968; Laugenie and Mercer, 1973; Mercer, 1976; Porter, 1981) there has been little study of the moraines themselves.

Some of the moraines of the Lake District show unusual features: great size, large amounts of associated outwash extending into the Central Valley, parallelism with lake shorelines, low longitudinal gradients of lateral moraines, and the presence of abundant reworked outwash material and deformed glaciolacustrine sediments within the ridges. This paper examines the moraines around Lago Puyehue and Lago Rupanco

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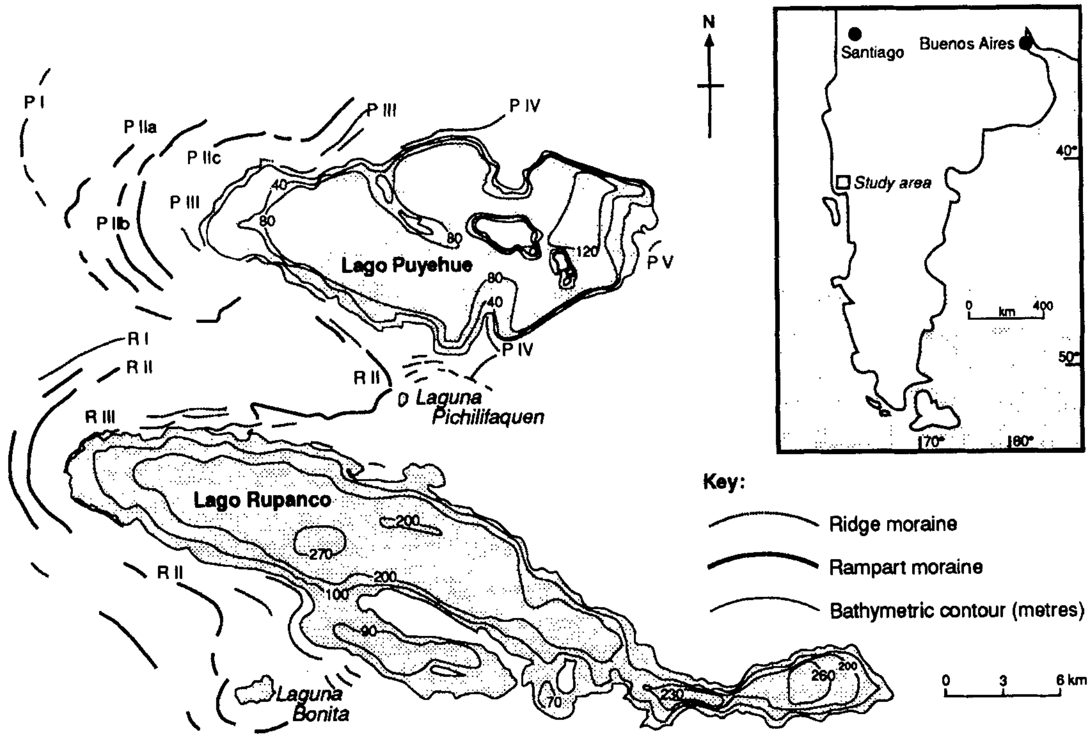


Figure 1. Schematic map of moraine sequences around Lago Puyehue and Lago Rupanco. Bathymetry from Campos *et al.* (1989, 1992) shows a submarine ridge connecting the north and south segments of the Puyehue IV moraine

in order to elucidate the processes responsible for their formation and thus provide insights into the relative importance of climatic and non-climatic controls on location, form and constituent sediments of the moraines.

MORPHOLOGY

Aerial photographs from the Instituto Geografico Militar were used to compile a preliminary geomorphological map at a scale of 1 : 50 000. Landforms were mapped in the field on the basis of their morphology, relative age and relations with other landforms. Exposed sections were logged and grain size distributions were measured.

The geomorphological map of Lagos Rupanco and Puyehue clearly shows that moraines are largely restricted to a narrow zone at the western ends of the lakes. The moraines occur as a nested sequence of arcuate segments (Figure 2) which are concentric around the lakes. The sequence is similar around both lakes. A few moraines are situated on the north and south shores of the lakes and one moraine lies in a side valley to the east of Lago Puyehue. The moraines can be divided into two types on the basis of form, position and constituent materials: *rampart* moraines are broad amalgamated moraine complexes made up largely of outwash, whereas *ridge* moraines are narrow, single ridges usually located around the present-day lakeshores (Figure 1).

Rampart moraines

These moraines are made up of a succession of closely spaced, arcuate ice-contact slopes which mark the proximal sides of a series of amalgamated outwash fans (Figure 3). Proximal slope angles are typically 6–9° and the slopes are from 30 to 40 m high. The area between each pair of ice-contact slopes comprises meltwater channels and kettle holes. Distal slope angles are low (<3°) and grade westwards into gently dipping

outwash plains (0·5–1·0°). The tops of the moraines are gently undulating with a cover of low mounds and hollows. The Rupanco II and Puyehue II moraines are between 2 and 5 km across. The outwash plains of Puyehue II and Rupanco II are contiguous with each other and with the outwash plains of Lago Llanquihue (to the south) and Lago Ranco (to the north). The Puyehue II moraine consists of three amalgamated ice-contact slopes with no intervening outwash between them. The threefold division is seen most clearly around the southwest margin of the lake. Similarly, the Rupanco II moraine is made up of more than one ice-contact slope.

Rampart moraines also occur besides both lakes. The lateral ramport moraines have a similar morphology but, where they have been deposited on sloping valley sides, they tend to be more closely spaced. The longitudinal gradients of the lateral moraines are shallow; at the western end of Lago Puyehue they rise eastwards with gradients of 1–2 m/km (0·05–0·1°) (Figure 4). Along the north shore of Lago Puyehue there is a marked change about 5 km from the west end of the lake. Here, longitudinal gradients become steeper towards the east (17 m/km (1°)) and the lateral moraines diverge from the lake. Rupanco lateral moraines show uniform gradients (*c*.12 m/km (0·7°)) throughout their length.

Ridge moraines

Ridge moraines differ markedly from rampart moraines in their form. Instead of broad, amalgamated complexes they are single, well-defined, sharp-crested ridges a few tens of metres high with slope angles of 8–20° (Figure 3). The ridge crests are breached by meltwater channels which lead into outwash plains. This morphology is exemplified by the Puyehue III moraine which can be traced for several kilometres around the lake; an equivalent moraine can be followed around the western end of Lago Rupanco. In addition to the lakeshore moraines, ridge moraines also occur distant from the lakes. The Puyehue I and Rupanco I moraines are largely buried by the outwash from the Puyehue II and Rupanco II moraine stages. They form ridges with narrow, sharp crests and similar dimensions to the other ridge moraines, Rupanco III, Puyehue III and Puyehue IV.

Lateral ridge moraines occur beside the lakes and have the same sharp-crested, single-ridge morphology as the terminal moraines but are closely spaced to form a stacked sequence of ridges. The Rupanco III, Puyehue III and Puyehue IV lateral moraines have low longitudinal gradients: the west end of Puyehue III is horizontal whilst gradients elsewhere are less than 0·5° (Figure 4). As with the rampart moraines, the north shore of Lago Puyehue shows a kink where gradients steepen and the moraines are aligned to the northeast. At this bend and change in long profile of the lateral moraine there is a large mound which rises *c*. 50 m above the ridge.

SEDIMENTOLOGY

The moraines are formed of three sedimentary facies: glaciofluvial, glaciolacustrine and till. Glaciofluvial sediments occur as thick sequences of well-stratified gravels with a sandy matrix. Individual beds are moderately sorted and laterally continuous for a few tens of metres. Clasts of cobble and pebble size are common and most clasts are rounded to well-rounded. Cross-stratified sand lenses up to 10 m across and 1 m thick are interbedded with the gravels. Glaciolacustrine sediment occurs as finely laminated clay and silt containing dropstones. Laminae are commonly submillimetre in thickness but can be up to 1 cm thick. The clay and silt occur as normally graded couplets. Subangular to rounded clasts up to 15 cm diameter deform the laminae below and are draped by overlying laminae. Each dropstone is commonly associated with a thin lens of diamict which extends either side of the clast and grades upwards into the overlying silt. Tills are composed of diamict with similar colour and clast composition to the glaciofluvial sediment but are poorly sorted and unstratified (Bentley, 1995). The tills also contain a small number of sub angular clasts over 1 m in size which are not present in the outwash. A key feature is that the tills contain blocks, up to 80 cm across, of the laminated glaciolacustrine sediment. They also contain clay as deformed laminations in small pockets around larger clasts and dispersed throughout the matrix. These sediments occur in broadly similar associations within each of the moraines. Glaciofluvial sediments comprise the bulk of each moraine and form thick sequences which can be traced distally where they grade into the shallow-dipping outwash plains. Glaciolacustrine sediment occurs as blocks within the tills and as a thin, deformed layer at the foot of the proximal

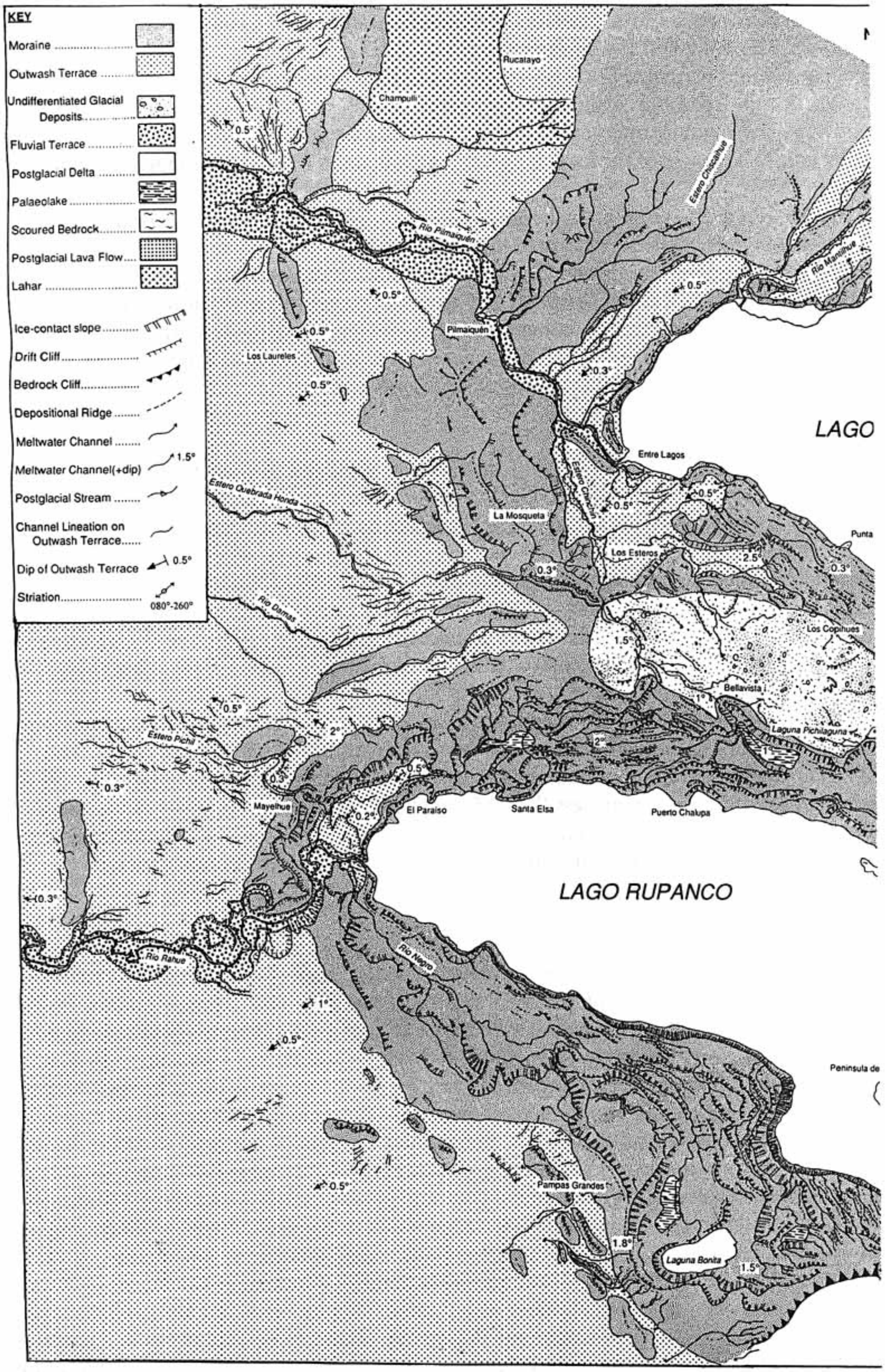
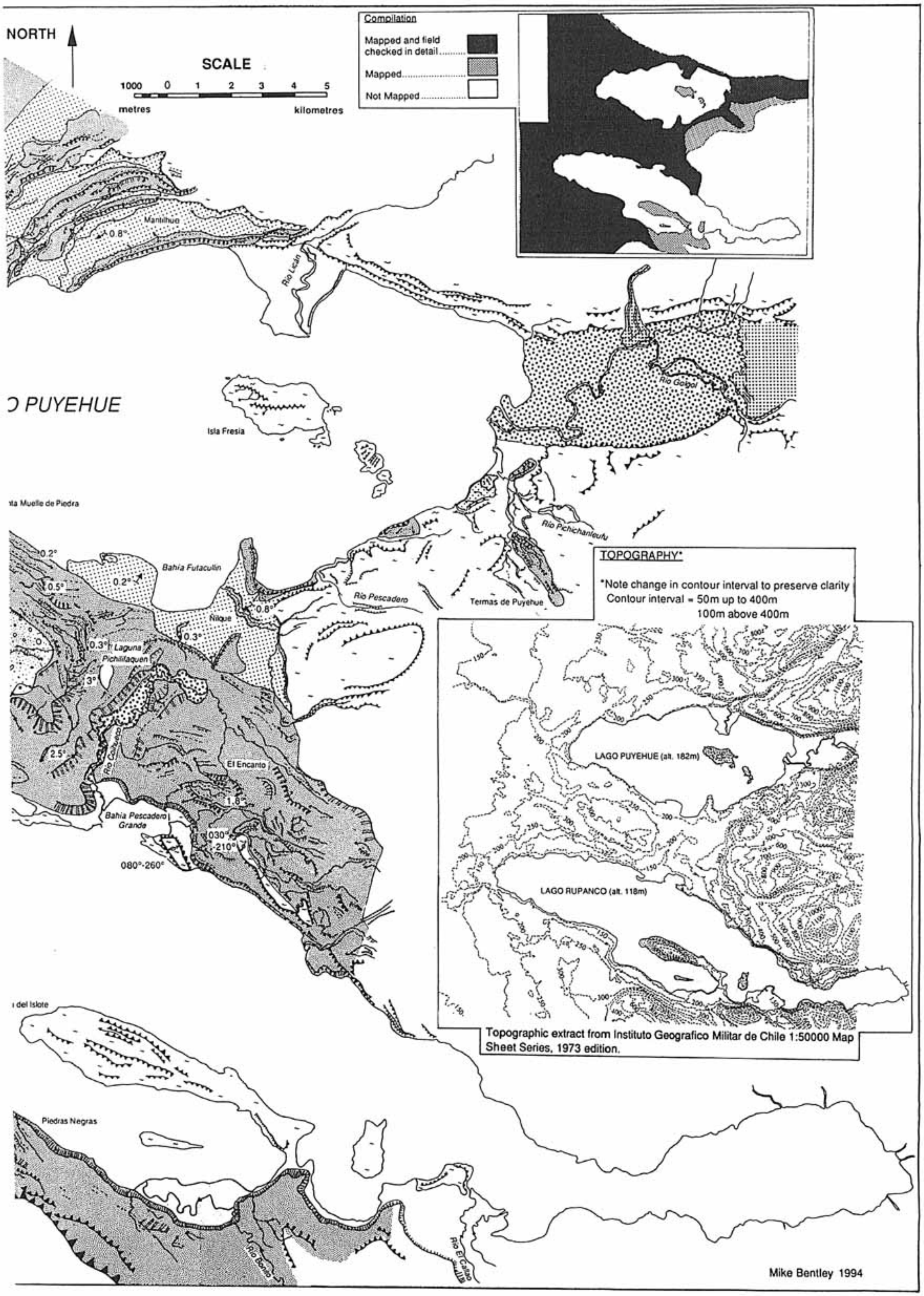


Figure 2. Geomorphological map of the environs of Lago Puyehue and Lago Rupanco. A nested sequence of amalgamated rampart moraines and single ridge moraines occurs around each lake. The mapping is based on field study of morphological relationships backed up by dating


NORTH
SCALE
1000 0 1 2 3 4 5
metres
kilometres
Compilation
Mapped and field checked in detail
Mapped
Not Mapped
Mantilhue
0.8°
Rio Licán
Rio Golgol
PUYEHUE
Isla Fresia
Rio Pichichanleufu
TOPOGRAPHY*
*Note change in contour interval to preserve clarity
Contour interval = 50m up to 400m
100m above 400m
Bahia Futacullin
0.2°
0.5°
0.2°
Rio Pescadero
Termas de Puyehue
Nilque
0.8°
0.3°
0.3°
Laguna Pichilifaquen
3°
2.5°
Rio Golgolito
El Encanto
1.6°
Bahia Pescadero Grande
030°
-210°
080°-260°
LAGO PUYEHUE (alt. 182m)
LAGO RUPANCO (alt. 118m)
Topographic extract from Instituto Geografico Militar de Chile 1:50000 Map Sheet Series, 1973 edition.
Piedras Negras
Rio Bonito
Rio El Callao
Mike Bentley 1994

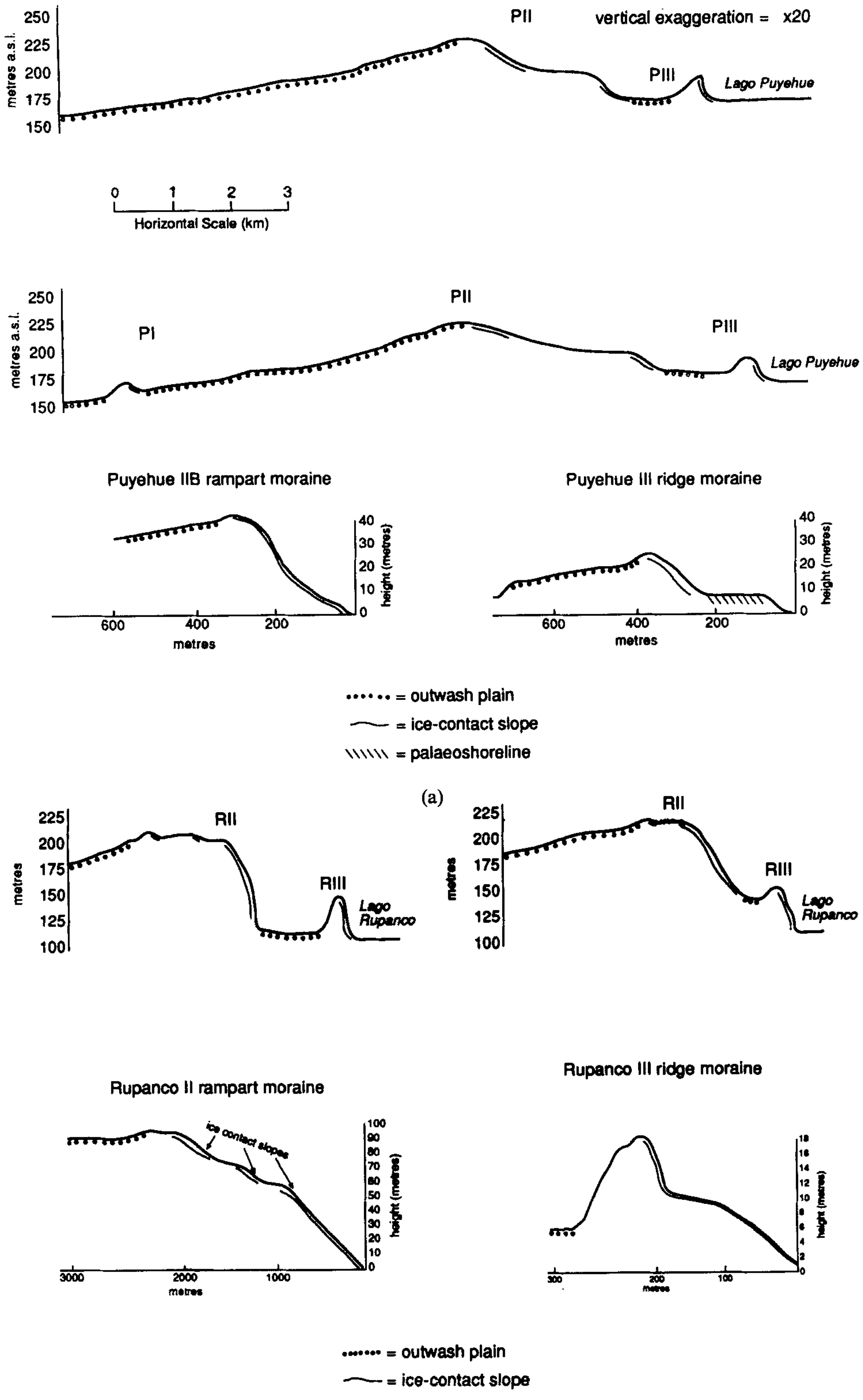


Figure 3. Surveyed profiles of moraines at the west end of (a) Lago Puyehue and (b) Lago Rupanco. There are strong contrasts between the morphology of rampart and ridge moraines. Rampart moraines are broader and are composed of a number of ice-contact slopes whereas ridge moraines are narrow single ridges

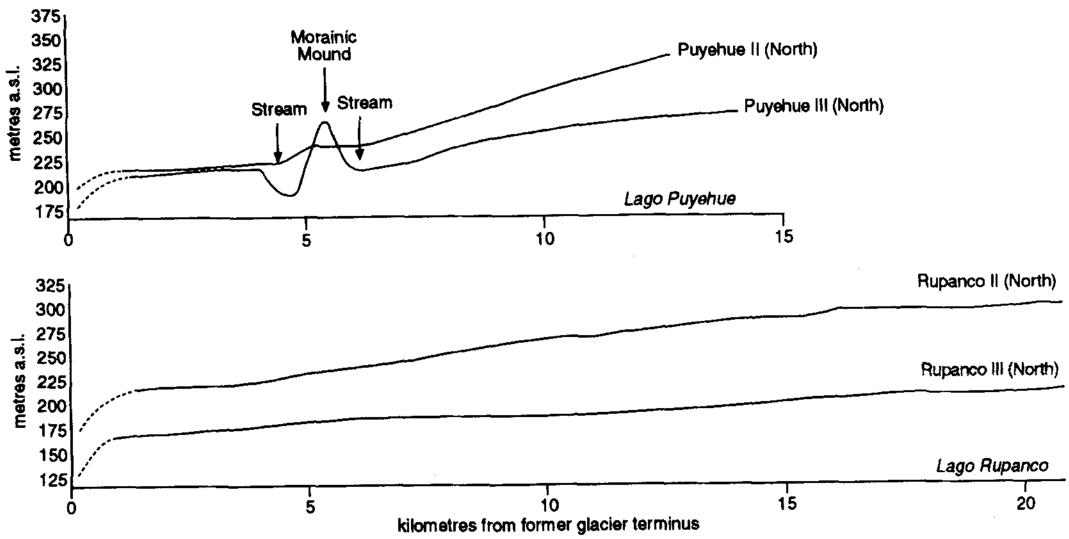
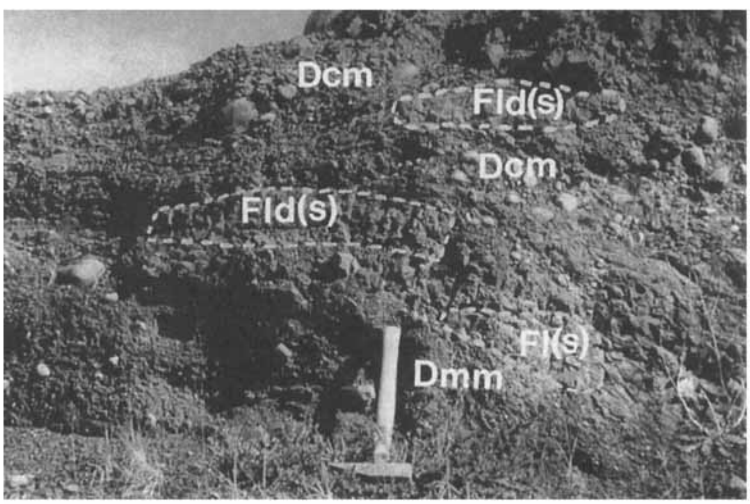


Figure 4. Longitudinal profiles of lateral moraines around (a) Puyehue and (b) Rupanco. Former snout positions are marked by the dotted lines. Longitudinal gradients are low around both lakes implying low-angle glacier profiles

slope of some moraines. The tills occur only on the proximal slopes of moraines where they form a layer 0·5 to 5 m thick overlying the glaciofluvial sediment. The contact between the till and glaciofluvial sediment can be sharp and erosional but is sometimes gradational and marked only by a progressive increase in clay content and decrease in stratification and sorting of the glaciofluvial sediment. Close to the contact the glaciofluvial beds are commonly folded.

Rampart moraines

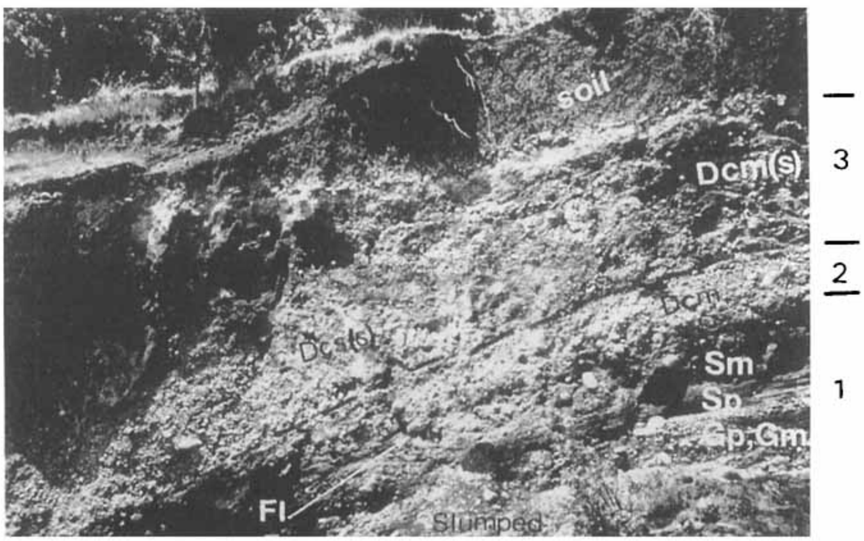
Three sections in the proximal ice-contact slopes of ramparts Puyehue IIB and Puyehue IIC demonstrate similar sediment associations. A section cut into the Puyehue IIB proximal slope exposes a 5 m thick clay-



(a)

rich diamict with a dip and weak clast fabric parallel to the slope which overlies 20 m of horizontally stratified glaciofluvial sediment. Below the contact the glaciofluvial beds show upright symmetric folding with fold axes aligned north-northwest. The folds are less pronounced towards the west and the beds more than 20 m from the contact are undisturbed. A quarry at the top of the Puyehue IIC ice-contact slope exposes a till overlying glaciofluvial beds with an unconformable contact. The till is generally massive but

(b)



(c)

Figure 5. (a) Diamict in Los Esteros quarry, at the top of the Puyehue IIC ice-contact slope. The diamict contains abundant blocks of stratified glaciolacustrine clays and silts. Ice flow was towards the observer. Hammer is 30 cm long. (b) Folding in glaciofluvial sediments on the distal side of the Puyehue IV moraine at Mantilhue. The edge of the outwash plain has been buckled up by glacier ice impinging on the moraine to the right. Section face is 4 m high. (c) Section in the distal side of the Puyehue IV moraine. A thick diamict overlies folded glaciofluvial sediment with an erosional contact and is composed of similar material with the addition of a clay component. Ice flow was from left to right. Section is 7 m high. Lithofacies codes from Eyles *et al.* (1983). Dcm, massive clast-supported diamict; Dcm(s), sheared; Dmm, massive matrix-supported diamict; Dcs(s), sheared stratified clast-supported diamict; Gp, planar cross-bedded gravel; Gm, massive or very crudely bedded gravel; Sp, planar cross-bedded sand; Sm, massive sand; Fl, laminated fines (silt and clay); Fl(s), sheared; Fld(s), sheared, with dropstones

contains blocks of deformed glaciolacustrine sediment (Figure 5a). The laminae within the blocks show both low-angle reverse and steep normal faults. These blocks are commonly aligned such that the top and bottom edges are parallel to the ice-contact slope. Also included within the diamict are small pockets of deformed, laminated clays and silts which tend to be closely associated with larger clasts. The section is capped by a number of erratic boulders lying at the crest of the ice-contact slope. The third section, at the foot of the proximal slope of Puyehue IIC, exposes a 2 m thick homogenous till with an even greater clay content than at the previous two sections. The till unconformably overlies stratified fluvioglacial gravels with a sharp planar boundary.

Ridge moraines

Despite the morphological differences between ridge and rampart moraines, the sediments and structures making up the ridge moraines show similar relationships to those of the ramparts. A number of sections into the Puyehue III, Puyehue IV and Rupanco III moraines illustrate these similarities.

The proximal slope of the Rupanco III moraine exposes lakeward-dipping fluvioglacial sands and gravels overlain by 1·5 m of glaciolacustrine clays and silts. These are recumbently folded and have shallow-angle thrusts cutting the laminae. Both the folds and thrusts are directed towards the west and the degree of deformation increases upwards through the unit which is massive in its upper 90 cm. A sharp contact marked by a layer of cobbles and sand separates the deformed glaciolacustrine sediment from a crudely bedded till composed of gravelly sand containing <6 cm clasts of laminated glaciolacustrine clays and silts. In other sections along the proximal side of the moraine the till is absent and the fluvioglacial sediment is overlain by a much thicker accumulation of sheared glaciolacustrine clays. In places the lamination has been replaced by foliation dipping parallel to the proximal moraine slope. The foliation is not axial planar to the folding and is likely to be shear-induced banding. Exposures in the proximal slope of the Puyehue III lakeshore moraine show a thin layer of deformed glaciolacustrine clays very similar to those seen on the proximal slope of the Rupanco III moraine. The crest of the moraine exposes till with clay-rich matrix and deformed inclusions of laminated clays up to 3 cm long. On the distal side of the moraine, beds of fluvioglacial sediment have been gently folded into upright, symmetric folds. A large quarry on the distal side of the Puyehue IV moraine shows clearly the change from the sediments of the moraine ridge to the outwash plain. The well-sorted and extremely porous beds of the plain have been buckled up into a steep-dipping orientation at the edge of the plain and are increasingly folded and thrusted towards the crest of the moraine (Figure 5b). The fluvioglacial beds are overlain unconformably by till (Figure 5c) with sheared sands and clay clasts near its base, grading up into matrix-supported sands, gravels and cobbles with occasional clast pavements. The clast size distribution and shape characteristics are very similar to those of the lowermost fluvioglacial strata. The till becomes more massive higher in the section and contains folded, discontinuous sandy layers interbedded with cobble-rich layers and occasional boulders. The sand lenses have complex truncating relationships and were deformed syndepositionally rather than being tectonically included in the diamict.

Common characteristics

At each of the sections in the ridge and rampart moraines the fluvioglacial sediment is overlain by till with an erosional contact; the till is composed of material with similar colour, clast size, shape and roundness characteristics to the glaciofluvial sediment. This relationship suggests that the origin of the two sediment types is closely linked. The folding below the contact in Puyehue IIB and Puyehue III and the truncation of bedding in the glaciofluvial sediments in most moraines imply that the tills are derived from reworking of the outwash. Deformation of the fluvioglacial sediment, such as the bulldozing of the Puyehue IV outwash plain, was more intense close to the proximal side of the moraine and was probably due to glaciotectonism by the glacier snout as the till was deposited. In places, the deformation continued during further sedimentation, resulting in folded sand lenses within the till. Further fluvioglacial sedimentation would have been likely and some of the upper sequences may have built up simultaneously with the tills. Particle-size analysis of the sediment matrices also implies reworking of the glaciofluvial and glaciolacustrine sediments to form the tills. The compositions of the till samples lie on a mixing line between the glaciofluvial sediments and the glaciolacustrine clays and silts (Figure 6). Those till samples which have the same composition as the

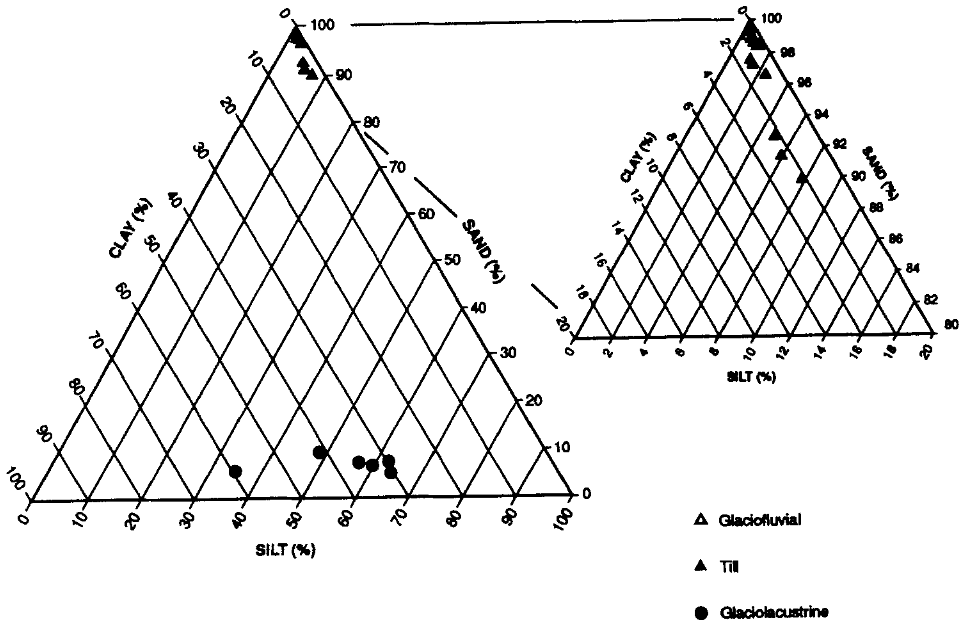


Figure 6. Grain size analysis of the matrix fraction of glaciofluvial, till and glaciolacustrine sediment from sites described in the text. (a) The till and glaciofluvial sediment contrasts with the clay- and silt-rich glaciolacustrine sediment. The analysis for entrained blocks of laminated sediments shows them to be dominated by silt (*c.* 35–65 per cent) and clay (*c.* 30–60 per cent) but with little sand content (<9 per cent) so the compositions lie close to the silt–clay axis. (b) Glaciofluvial sediments are composed dominantly of sand (98–100 per cent) with little silt (<2 per cent) and clay (<2 per cent). On the sand–silt–clay plot they tend to cluster close to the sand apex. The results for the diamicts from the same localities show a wider spread of values with more silt (<10 per cent) and clay (<4 per cent) but still dominated by sand. Many diamict compositions are very similar to the stratified material but the rest lie along a line extending towards the silt–clay axis

glaciofluvial material have been sheared enough to obliterate the stratification but have not been mixed with fine-grained material, whereas others have been mixed with glaciolacustrine sediment. The general position of the diamicts near the glaciofluvial end of the mixing line reflects a higher proportion of pre-existing glaciofluvial sediment than transported glaciolacustrine material.

The blocks of glaciolacustrine sediment contained in most of the tills lie up to 45 m above present lake level. The obvious source for this glaciolacustrine sediment is the Lago Puyehue basin, no more than a few kilometres from any of the sections in which it occurs. Transport by glacier ice is the most likely mechanism for the deformation and emplacement of the blocks, particularly as the tills occur on the proximal slopes of moraines. Therefore, the process of mild glaciotectonism by the ice margin suggested by the folding in the outwash was also accompanied by emplacement of glaciolacustrine sediment. The intact blocks predominantly show brittle deformation rather than extensive folding and are subparallel to the moraine slope. Probably they were frozen on to the base of the glacier in the lee of irregularities or derived from thrusting of frozen patches of the bed. The continuum of fine-grained sediment in the till from laminated intact blocks to deformed laminae to dispersed clay and silt suggests that some of the entrained glaciolacustrine sediment was deformed or redistributed during transport or as it was deposited in the till.

ORIGIN OF THE MORAINES

Despite their obvious size and morphological differences the rampart and ridge moraines have two key features in common. Firstly, both types were formed by a process which involved advance of a glacier snout into pre-existing outwash, with consequent mild glaciotectonism. The tectonism seems to have been largely restricted to the proximal sides of the moraines, implying that once the glacier impinged on the outwash it

did not advance very much further. This was accompanied by reworking of fluvioglacial strata to form an overlying till. This till contains deformed glaciolacustrine clays and silts derived from the up-glacier lake basin. A second important similarity of the two moraine types is that both types are associated with low longitudinal gradients of their lateral moraines.

One possible explanation for the low gradients of the lateral moraines, the deformed sediments within the moraines and the presence of glaciolacustrine sediments is that the glacier was advancing over a deforming bed. Boulton and Jones (1979) highlighted the importance of a deforming substrate below temperate ice. They observed that a large proportion of the forward movement of a glacier can be due to deformation of the sediment rather than the glacier. This led to the development of a model in which the glacier surface profile and forward movement are controlled by the strength and hydraulic properties of the bed sediments, although other factors such as subglacial hydrology and bedrock sticky spots may also play a significant role (Humphrey *et al.*, 1993; Kamb, 1991). When hydraulic transmissibility is high, subglacial water pressures are relatively low and deformation of the bed is unlikely. If, however, the sediment has a low hydraulic transmissibility then porewater pressures build up until deformation of the bed occurs. This leads to a lower glacier surface profile. In the case of the southern margin of the Laurentide Ice Sheet, gradients may have been as little as one-sixth those of typical profiles from present-day ice sheets. This view has been supported by seismic observations on Ice Stream B, Antarctica, which suggest that ice is moving on a subglacial sediment layer deforming at an extremely low effective stress (Alley *et al.*, 1986; Blankenship *et al.*, 1986).

The criteria necessary for bed deformation are high subglacial water pressures, and sediment with low shear strength. Porewater pressures tend to be raised in saturated impermeable sediments; for example, clays and fine silts tend to be relatively impermeable and susceptible to deformation whereas gravels commonly have high permeabilities and are resistant to shear deformation. Thus, glaciolacustrine sediment is ideal for bed deformation since there is abundant water lying over the sediment of the lake bed and this sediment is usually fine-grained and impermeable so little porewater can escape. The material will be saturated and, if a load is applied, pore pressures will rise and the sediment will deform easily. The fine-grained glaciolacustrine silts and clays of the Puyehue and Rupanco moraines would have been ideally suited to bed deformation. Any direct observation of deformed sediment in the former subglacial zone is prevented by the lakes but the low gradients of lateral moraines around both lakes demonstrate shallow glacier profiles, whilst the tectonized glaciolacustrine clays and silts on the proximal sides of moraines suggest that the glaciers advanced over, and deformed, a bed of fine-grained sediment. Therefore, a deforming bed origin agrees with the existing evidence.

Alternatively, these features could be related to surging glaciers or ice shelves. However, the Puyehue and Rupanco moraines show few of the features commonly associated with surges, such as looped and accordion-style folding, extensive glaciotectonism, normal faulting in moraine cores, water escape structures and chaotic 'dead ice' topography (Sharp, 1988) and so this origin can probably be discounted. Horizontal moraines formed by existing and former ice shelves have been reported from the Arctic (England *et al.*, 1978) and Antarctic (Sugden and Clapperton, 1981) regions. However, the location of the Puyehue and Rupanco glacier termini at a low altitude in a mid-latitude area with high precipitation means they would have been temperate glaciers and the ability of temperate ice to form floating shelves is controversial (Powell, 1991). The apparent lack of temperate ice shelves and the effect of intercrystalline water films on the strength of ice suggest that temperate ice is simply not strong enough to form an ice shelf (Powell, 1991). Post (pers. comm.) refutes this and argues that there are examples of apparently floating temperate ice tongues (e.g. Bering glacier) and that it is the fracturing of fast-moving ice and the higher temperatures of temperate seas which explain the lack of temperate ice shelves. A change in glacier behaviour is suggested along the north shore of Puyehue where gradients alter down-glacier from shallow to near-horizontal. The Puyehue III moraine is similar to ice-shelf moraines both in terms of its horizontal, narrow, single-ridge form and the mixture of exotic and local sediment (Sugden and Clapperton, 1981), so it is possible that near its terminus the Puyehue ice may have been sufficiently thin to float and form a horizontal moraine around the shoreline. However, this origin cannot be confidently ascribed to the Puyehue III moraine until the debate on floating temperate ice is resolved.

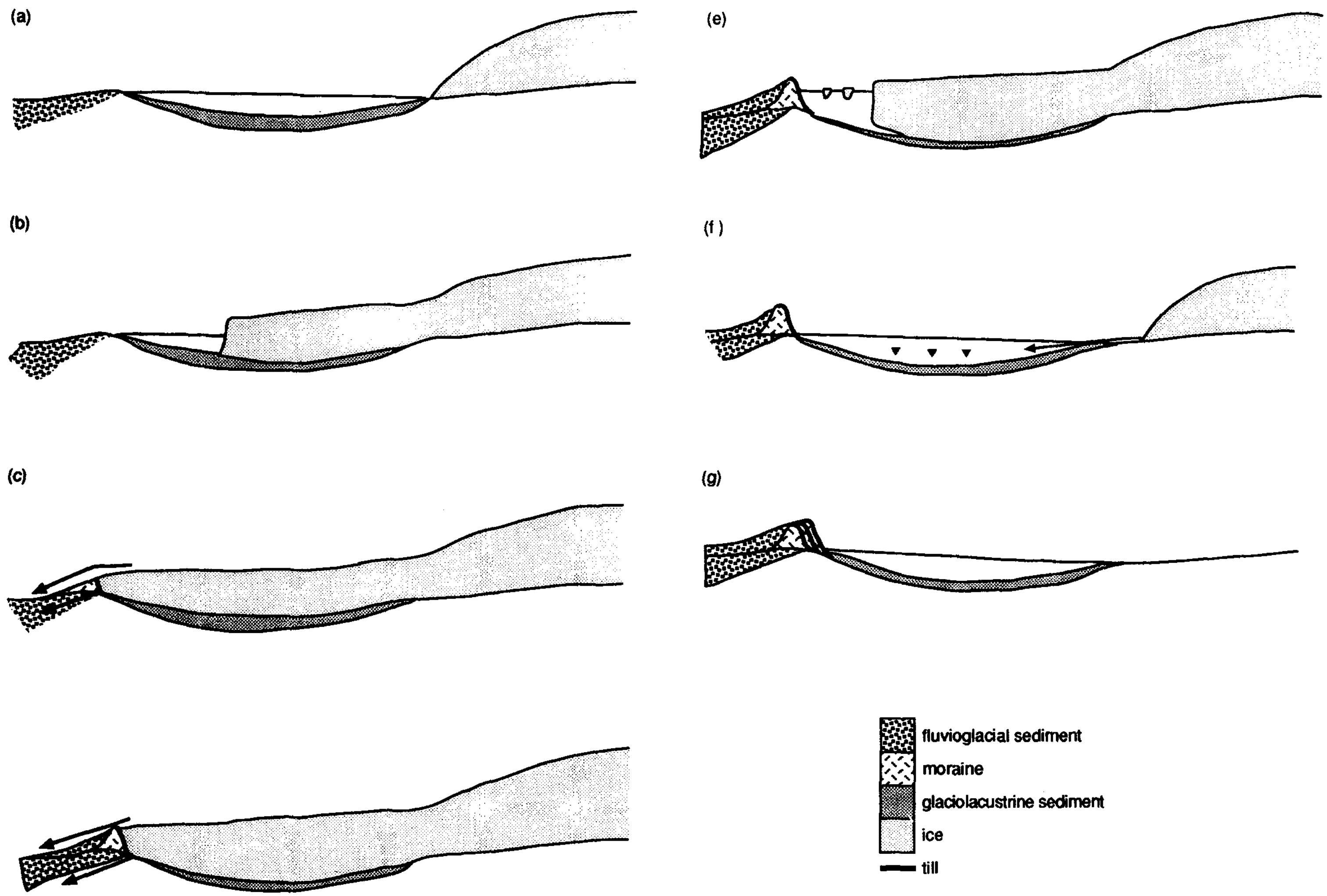


Figure 7. A model for the formation of shoreline moraines. The sequence of cross-sections refers to a single cycle of glacier advance and retreat. (a) The glacier advances down the trough towards the lake with a 'conventional' convex glacier profile. (b) The glacier advances into the lake and encounters a bed of saturated impermeable sediment. This wet sediment with high pore pressures is deformed and the surface profile lowered. (c) The snout reaches the west end of the lake where pre-existing glaciofluvial deposits are more resistant to deformation. Basal water drains easily so pore pressures are lower, bed deformation does not occur and the snout halts. Mild glaciotectonism occurs. (d) Longitudinal compression causes the glacier to thicken. Glaciotectonism continues as glaciofluvial sediment builds up. The glacier may actually leave the basin given sufficient climatic forcing. (e) The onset of retreat with calving into the lake leading to rapid retreat with halts only at pinning points. (f) The snout lies up-valley of the lake and lacustrine sediments are topped-up by distal sedimentation. (g) Feedback can lead to the formation of amalgamated moraines

A MODEL FOR THE FORMATION OF RAMPART AND RIDGE MORAINES

A single model incorporating the processes of advance over a deforming bed into outwash and glaciotectonism can explain the formation of both rampart and ridge moraines. The model can be divided into a six-stage cycle (Figure 7).

Stage 1: In the early stages of advance the glacier lobe moves down the glacial valley towards the lake. It has a conventional longitudinal profile with angles behind the snout of 2–3°.

Stage 2: When the glacier reaches the lake it encounters a bed of saturated, fine, impermeable sediment. This material is more readily deformed than the ice itself and allows the glacier to advance easily with little internal deformation of the ice (Boulton and Jones, 1979). Thus the portion of the glacier in the lake adopts a flatter longitudinal profile with gradients of less than 1°. Any calving at the glacier front is insufficient to offset the amount of forward movement over the deforming bed and so the snout advances. If the ice becomes sufficiently thin then it may achieve flotation to form an ice shelf.

Stage 3: At the west end of the lake the snout encounters pre-existing coarse-grained fluvioglacial sediments deposited during retreat from previous glacial advances. Basal water drains more easily through these gravels so pore pressures are lower and the bed is less susceptible to deformation than the glaciolacustrine sediment over which the glacier has been advancing. Surface gradients are so low that the basal shear stresses are insufficient to deform the ice internally and allow its further advance, at least until the lobe thickens massively. Modest deformation occurs in this zone of compressive flow where flow over saturated, deforming clays gives way to flow over well-drained outwash. The pre-existing fluvioglacial strata are folded and, in places, thrusted. In the course of this deformation fluvioglacial gravels and clays derived from the lake basin are tectonically reworked to form a thin veneer of till. However, the deformation is mild and tends to be restricted to the proximal side of the moraine. The glacier tongue now provides a direct conduit for meltwater onto the outwash plain to the west. As more fluvioglacial strata are deposited then the barrier to further advance thickens.

Stage 4: The longitudinal compression at the snout causes the glacier to thicken and the profile to steepen at the west end of the lakes. Eventually the glacier may thicken sufficiently to leave the basin but this possibility is restricted by the simultaneous build-up of fluvioglacial material on the distal side of the moraine. Small amounts of deformation may continue as shear stresses increase so the tills formed in Stage 3 may be further deformed.

Stage 5: Once the glacier retreats from its position at the west end of the lake it will calve into deeper and deeper water. This is likely to have a runaway effect and the glacier will experience rapid calving retreat until it stabilizes at the east end of the lake, or at a suitable pinning point (Mercer, 1961). This leaves a lake shoreline moraine with low lateral gradients, made up largely of outwash and an overlying melange of glaciolacustrine and fluvioglacial sediments.

Stage 6: During the time the glacier terminus lies at, or beyond, the east end of the lake the clays and silts will be topped up by further sedimentation. This sedimentation could be in a glacier-contact or distal lake, depending on the position of the terminus relative to the lake (Ashley, 1988).

The six-stage cycle will be repeated for each glacial advance and once the first moraine has formed there is strong potential for feedback during subsequent advances. There are two reasons for this. Firstly, the presence of a ridge at the end of the lake forms another barrier to advance, in addition to the contrast in bed conditions, and secondly, the lake allows the further build-up of saturated fine-grained sediment which contrasts strongly with the permeable fluvioglacial sediment at the westend. Thus, any subsequent advance is likely to reach the same place, even for a wide range of mass balance conditions. This self-reinforcing process leads to the construction of an amalgamated moraine in a location determined by the initial lake shoreline position.

If retreat from a previous moraine position is accompanied by partial infilling of the western end of the lake by coarse, permeable meltwater deposits then this moves the grain-size and permeability boundary into the lake. Thus the next moraine location is likely to be developed further up-glacier. This may have occurred in the case of the Puyehue III advance which did not reoccupy the inner ice-contact slope of the

Puyehue II amalgamated moraine but rather formed a new single ridge. In effect the rampart moraine is a special case of a ridge moraine in which several advances of the same type have formed a large amalgamated complex. Alternatively, the ridge moraine (e.g. Puyehue III) can be viewed as being in the incipient stages of forming a rampart moraine. Whichever way it is viewed it is crucial to realize that despite their outwardly dissimilar appearances, the two moraine types were constructed by the same process of glacier advance over a deforming bed of lake sediment. This model is most likely to operate where glaciers flow from confined valleys into relatively broad lakes. Lake shoreline moraines would be less likely to form in narrow, steep-sided valleys where sidewall drag would exert a strong control on glacier movement.

IMPLICATIONS

This model of moraine formation has four major implications. Firstly, feedback between the glacier and the bed influences its subsequent behaviour. An initial moraine may be sufficient to dam a lake and create a distinction between glaciolacustrine and glaciofluvial sediments where there are marked contrasts in permeability and shear strength. Subsequently, it is this moraine which dictates the extent of the next advance and so the position of subsequent moraine accumulation. The more moraines formed at this location, the greater the control it exerts on later glacial advances. This feedback control will only be overcome by prolonged, large glacial advances.

Secondly, moraine sediments and locations in this area were clearly subject to non-climatic controls. A climatic trigger is still necessary to cause a glacier to advance as far as the lake, but how far it gets beyond this depends largely on the distribution of sediment. This is another example of the way in which topography and the nature of the glacier bed can influence glaciers. This may explain why the moraine sequences around each of the Chilean Lakes are so similar and so clustered.

The role of lakes in influencing glacier fluctuations is important. The lake is controlling glacier dynamics at a local scale and can exert a stronger control on glacier position than the mass balance. This local lake effect can be compared to tidewater calving, where a non-climatic calving cycle can dominate regional mass balance (Mercer, 1961). Also, the intuitive assumption that moraine locations define and dam lakes can be challenged. Here, it is the initial lake shoreline that determines the position of the subsequent moraines and not vice versa.

The fourth implication is that conditions favourable for shoreline moraines are most likely to exist at the snouts of temperate glaciers where high debris content and large amounts of meltwater favour substantial barriers of fluvioglacial outwash and enhance the grain-size contrasts by depositing coarse sediment in front of the glacier during stadials and fine-grained sediment in the lake during interstadials. Possible Pleistocene analogies for the moraines described in the Chilean Lake District include the moraine loops around the southern ends of the North American Great Lakes, the loops around the Italian and South German Lakes, and some termini on the west side of the Southern Alps, New Zealand.

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